

Decision support systems for dam planning and operation in Africa

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Summary

Dams are amongst the most important components of water resource systems. In many places the water regulated by and stored in dams is essential to meet the development objectives of water supply, agriculture (i.e. irrigation and livestock), industry, energy generation and other sectors. However, in the absence of adequate foresight and planning for adverse impacts, past dam construction has often resulted in devastating effects for ecosystems and the livelihoods of affected communities. Participation of stakeholders in the decision-making process and increased equity in the distribution of benefits are pre-requisites to mitigating dam related conflicts and ensuring sustainable projects. Appropriate use of decision support systems to assist in the planning and operation of dams can contribute to these objectives and can also enhance gains in economic, social and environmental benefits.

Keywords:

Dams, decision support systems, stakeholder participation, sustainable development

Introduction

Recently there has been increased focus on the development of infrastructure to assist in meeting future human water needs, particularly in Africa. Currently 64% of the total population of Africa relies on water resources that are limited and highly variable and 75% of the continents cropland is located in arid and semi-arid areas, where irrigation can greatly improve productivity and reduce poverty (Vorosmarty *et al.*, 2005; Smith, 2004). Furthermore only 4.8% of the continents potential hydropower is currently exploited (Gopalkrishnan, 2004). Of the 45,000 large dams worldwide only 1,039 are located in sub-Saharan Africa (WCD, 2000). Dam proponents argue that dams enable better water management and that modest increases in water use, made possible by dams, could significantly reduce constraints on economic development, pollution and challenges to human health (Bartle, 2004; Commission for Africa, 2005). It is probable that investment in new dams in Africa will increase in the immediate future (World Bank, 2004). Indeed, several large dams are currently being planned or constructed (Table 1).

With increasing water demand and greater awareness of environmental concerns and social responsibilities, the complexity of dam planning and operation has increased greatly in recent years. It is no longer acceptable to optimize dam operation on the basis of economic criteria alone. In its report, the World Commission on Dams (WCD) called for a more equitable distribution of the benefits to be gained from large dams and proposed the inclusion of all identified stakeholders in the planning and management of

water resources stored in reservoirs (WCD, 2000). To achieve this dam managers must take account of water uses upstream and downstream of the dam and must also give consideration to political, organizational, social and environmental factors, not only biophysical constraints. However, in any specific situation, the relationships between these different elements are not well understood (i.e., the problems are *ill-structured*) and this makes decision-making extremely difficult.

Table 1: *Examples of large dams planned or being constructed in Africa*

Name	Country	River	Primary Purpose
Rusumo Falls	Tanzania	Kagera	Hydropower
Bujagali	Uganda	White Nile	Hydropower
Mphanda Nkuwa	Mozambique	Zambezi	Hydropower
Bui	Ghana	Black Volta	Hydropower
De Hoop	South Africa	Steelpoort	Water supply to mines and irrigation and to maintain environmental flows
Skuifraam	South Africa	Berg	Water supply
Mutonga/Grand Falls	Kenya	Tana	Hydropower, irrigation, water supply and prevention of seawater intrusion.
Merowe	Sudan	Nile	Hydropower and possibly irrigation
Tekeze	Ethiopia	Blue Nile	Hydropower
Gilgel Ghibe	Ethiopia	Omo Ghibe	Hydropower
Tendho	Ethiopia	Awash	Irrigation
Kesem	Ethiopia	Awash	Irrigation

In recent years considerable effort has gone into developing decision support systems (dss) to assist water resource managers to make well-informed decisions. Many of these help structure decision processes and support the analysis of allocation problems involving complicated hydrological, environmental and socio-economic constraints and conflicting management objectives. Some dss also promote understanding of system dynamics and a few facilitate the communication of information to people without technical abilities, so that they can participate more fully in the decision-making process.

This paper reports on the establishment of a study that is investigating the applicability of linking tools/methods for social appraisal/stakeholder involvement and contemporary dss in the planning and operation of dams. It comprises: i) a brief review of the issues that need to be considered in dam planning and operation; ii) a preliminary review of decision support systems; and iii) a brief description of the project being conducted. It concludes with four key principles for the use of dss in dam planning and operation.

Review of the issues

The construction of a dam requires an investment of financial capital the result of which is a series of new entitlements that are distributed, either through political-administrative or market mechanisms, to members of society. At the same time, the construction of a large dam has a profound effect on the natural and social landscape of the catchment in

which it is located. These changes affect the legal, customary and *de facto* entitlements to natural resources, environmental quality and social-cultural integrity experienced by local communities living both upstream and downstream of the dam (Beekman, 2002).

In the past, planning of dams and their operation focused primarily on meeting future demand (i.e., for water, power or irrigation) through identification of the least-cost option. Cost-benefit analysis (CBA) emerged between the 1950s and 1970s as the dominant economic tool for supporting decision-making on dam projects (Beekman, 2002). If the expected benefits of a dam were deemed to outweigh the predicted costs the project went ahead. The relatively narrow nature of the technical and economic analyses undertaken did not necessarily mean that decision-makers that chose dams as a development option were unaware of the social and environmental costs. However, often the sacrifices were deemed to be acceptable in light of the benefits that would accrue.

Ill-planned resettlement of people from the area flooded by the reservoir is usually the cause of the impacts which have the most significant adverse social impacts of a dam construction. For example, the Tonga people displaced by the construction of the Kariba dam on the Zambezi River in the 1950s are still seeking adequate compensation for loss of livelihoods (Tremmel, 1994). However, there are also many documented cases of dam operation adversely affecting the livelihoods and health of people, living not just in the immediate vicinity of the dam, but sometimes many hundreds of kilometers downstream. Adverse impacts occur both directly and through effects on the environment (Table 2).

In many cases decisions pertaining to dams have been made in isolation by governments and funding agencies without any form of public consultation. In many cases information was deliberately withheld from concerned groups and little or no consideration was given to objections of local people. In recent years this form of decision-making has fueled controversies and opposition and in some instances led to large-scale conflict which has resulted in considerable delay, or even the abandonment, of major dam projects (WCD, 2000).

Dam planning and operation can be characterized as an exercise in conflict resolution (Jamieson, 1986). Conflicts pertaining to dam planning and operation are primarily clashes of interest between human resource users with competing concerns. As such they are socially complex problems and typical of disagreements that arise from human distribution of limited natural resources. These conflicts are characterized by (Bruckmeier, 2005):

- divergence in values, needs and interests of individuals or social groups
- different and subjective perceptions, valuations and interpretations of “facts”¹
- disagreements in which cultural, social, economic and ecological dimensions are intertwined

¹ For large dams this is further complicated because many facts, particularly in relation to ecological impacts and the possible knock-on effects on livelihoods are uncertain and cannot be resolved without long and costly research investigations.

Table 2: *Examples from Africa of adverse livelihood impacts, attributed to dam construction and operation*

Location	Impacts
Kafue Flats, Zambia	Changes in flow regime downstream of the Itzhi-Tezhi dam have resulted in (Acreman <i>et al.</i> , 2000): <ul style="list-style-type: none"> - loss of traditional flood recession garden systems - decreases in grazing resources as a result of changes to vegetation on the floodplain and increased dry season inundation - a change in fish species and increase in catch effort due to larger areas of dry season open water - a decrease in households supported by fishing from 2,600 to 1,150 between 1977 and 1984
Senegal Delta, Senegal	Changes in the flow regime caused by construction of the Diama dam on the Senegal River delta have resulted in (Duvail and Hamerlynck, 2003): <ul style="list-style-type: none"> - collapse of livelihoods dependent on fisheries - loss of livestock grazing through reduced flood dependent pasture - loss of vegetation previously extensively used for mat making
Tana River, Kenya	Changes in flow regime downstream of dams on the Tana river have resulted in (JICA, 1997): <ul style="list-style-type: none"> - decline in riverine pasture - increasing pressure on common pool resources shared by farmers and pastoralists - acceptance and increased reliance of local people on state authority which is rendering tribal and inheritance-based customary systems of regulated access to floodplain farm and grazing resources increasingly redundant
Atbara River, Sudan	Drought and changes in flow regime downstream of dams on the Atbara River in Sudan have resulted in (Abdel Ati, 1992): <ul style="list-style-type: none"> - dereliction of traditional irrigation methods and increased share-cropping arrangements between farmers and diesel pump owners - decline in households involved in agriculture from 92% to 81% between 1964 and 1989 - disappearance of fishing and wood collection as livelihood strategies - greatly increased out-migration as result of the reduction in cultivable land
Hadejia-Jama'are Rivers, Nigeria	Reduction of flooding in the Hadejia-Nguru wetlands due to upstream dam construction, has resulted in (Barbier <i>et al.</i> , 1993): <ul style="list-style-type: none"> - reduction in agriculture (e.g. rice) - loss of grazing resources (mainly cattle of the Fulani people), decrease in non-timber forest products, fuel wood and fishing for local populations - reduction in the economic value of production in the wetlands, which analysis indicates is in total many times greater than that derived from the irrigation schemes for which the river has been dammed.
Volta River, Ghana	Construction of the Akosombo dam in Ghana resulted in (Gyau-Boakye, 2001): <ul style="list-style-type: none"> - increased incidence of many water borne diseases including schistosomiasis, malaria and onchocerciasis, in lakeside villages and those downstream of the dam - increased salinity in water supply for some towns, downstream of the dam - decline in economic activities as a result of loss of agricultural land - breakdown in traditional social order, in part because of the loss of ancient sacred places.
Logone Floodplain, Cameroon	Construction of the Maga dam in Cameroon resulted in (Mouafo <i>et al.</i> , 2002): <ul style="list-style-type: none"> - growing disputes between various interest groups, over access to water - collapse of fisheries due to loss of floodplain habitat - degradation of soils and pasture due to lack of silt inputs to the floodplain - 40% decrease in population of the floodplain as people have moved away

Clearly such conflicts can be very difficult to resolve. However, in relation to large dams there is wide-spread awareness of the need to mitigate conflicts as far as possible, in order to avoid bad publicity and the costs of delay. To this end, there is increasing understanding of the need for negotiation and participation based approaches that minimize conflict. Furthermore, issues of equity have come to the fore and it is now widely accepted that a necessary condition for sustainable development is recognition of the entitlements and sharing of the benefits of schemes with directly affected people (WCD, 2000). Therefore, a key goal of any large dam must be to ensure that it provides a development opportunity for all (i.e., all individuals and communities affected by the development gain sustainable benefits) (Table 3). Similar sets of guidelines have been developed to articulate environmental safeguards.

Table 3: *Guidelines on local outcomes that should be achieved by large dams* (modified from IHA, 2004)

1	Provide affected communities with improved living conditions
2	Improve public health conditions for impacted communities
3	Ensure equitable distribution of the benefits of the project, particularly to affected and vulnerable communities, through process such as revenue sharing, training programs and educational outreach
4	Ensure that the local knowledge of communities and stakeholders is utilized in project-planning
5	Support additional community infrastructure associated with the project, particularly water and electricity connection, where positive benefits to the community will result
6	Ensure that displacement is dealt with in a fair and equitable manner

This requires that dams are planned and operated in a different way to the past, with much greater emphasis on meeting local needs and, as far as possible, with full consideration of all hydrological, ecological and socio-economic factors.

State of knowledge and of practice

Dam planning and operation requires decisions to be made about the magnitude and timing of releases. Determining optimum reservoir storage capacities and operating regimes has been a major focus of water agencies, responsible for the planning, design and operation of dams, for many years (Yeh, 1985). Over the last 30-40 years major advances have been made in the development and use of a wide range of tools to assist in the planning and management of complex water resource systems (Jamieson, 1996).

Currently, the vast majority of reservoir system planning and operation is undertaken using simulation and optimization models (e.g., Lund and Guzman, 1999; de Monsabert *et al.*, 1983). To date these have focused primarily on the physical aspects of the system (Reitsma, 1996). They are frequently based on simple engineering principles for dam operation, such as keeping reservoirs full for water supply or empty for flood control. As such they provide a great deal of flexibility in the specification of system operations under various flow, storage and demand conditions. Many rules are based on largely empirical or experimental success, determined either from actual operational performance, performance in simulation studies or optimization results.

Reservoir operating policies are frequently defined by *rule curves* that specify either reservoir (target) storage volumes or desired (target) releases based on the time of year and the existing storage volume in the reservoir. Reservoirs can have multiple rule curves made up of wet season refill curves and dry season drawdown curves. The rule curves that regulate the releases and drawdown of a reservoir are referred to as control rules (Thorne *et al.*, 2003). For example, until recently a simple rule curve has been used for optimizing releases from the Itzhi-tezhi dam on the Kafue River in Zambia (Figure 1). This rule curve was developed with the sole objective of guaranteeing “firm”, and simultaneously maximizing “secondary”², hydropower production.

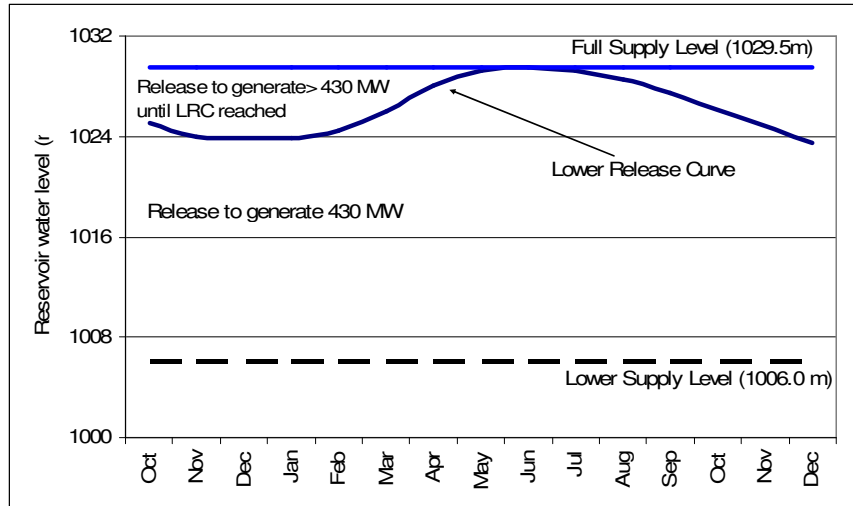


Figure 1: Rule curve for Itzhi-tezhi Dam on the Kafue River, Zambia

For most large dams, at any given time there may be a huge number of possible release options. The need to consider multiple, and often conflicting, objectives for a large number of stakeholders, and across a broad spectrum of scales, means that thousands of decision variables and constraints may need to be considered. It is in such cases that dss can greatly assist decision-makers.

Dss are intended to provide water resource managers with assistance in making rational choices based, as far as possible, on an objective assessment of issues. They may be used to assist with both strategic planning and management/operation control. There is no common definition of a dss. Some definitions, and perhaps the most widely accepted, refer specifically to computer tools. For example:

Dss are computer based tools having interactive, graphical and modeling characteristics to address specific problems and assist individuals in their study and search for a solution to their management problems (Loucks et al., 1991).

² Firm energy is the amount of energy that can be guaranteed with a specified degree of reliability and for a specified time period. Secondary energy is the amount generated in excess of firm energy. Secondary energy is variable and unpredictable; zero at times and large during periods of above average flow.

Similarly Reitsma *et al* (1996) define dss as:

Computer-based systems that integrate the following three components into a single software implementation

- *State information – data which represents the water resource system’s state at any point in time*
- *Dynamic and process information –first principles governing the resources behavior over time*
- *Plan evaluation tools – utility software for transforming raw system data into information relevant for decision-making*

Numerous researchers have developed computer based dss for the management and operation of reservoirs and river systems (e.g., Simonovic and Savic, 1989; Jolma, 1994; DeGagne *et al.*, 1996; Koutsoyiannis *et al.*, 2002). There are many examples of computer based dss being used for water resource management and specifically dam planning and operation in Africa. Many focus primarily on optimizing releases for one particular sector (e.g. hydropower) but others encompass broader aims and objectives (Table 4).

Table 4: *Examples of computer based dss used for water resource planning in Africa*

DSS	Description
Lake Victoria Decision Support Tool (LDVST)	Database, utility tools (i.e. to process and prepare data) and control models have been combined to support long range planning and short range operation of the Lake Victoria reservoirs and hydropower units. The primary function remains optimization of hydropower production.
Decision Support Systems for the Senegal River Delta	The hydrodynamic model MIKE-11, has been used in conjunction with a digital elevation model, to assess hydraulic functioning of different release regimes on the Senegal River delta and the consequent implications for the ecology and hence livelihoods of local people (Duvail and Hamerlynck, 2003).
The Nile Decision Support Tool (Nile DST)	Developed as part of the Nile Basin Water Resources Project to objectively assess the benefits and tradeoffs associated with various water development and sharing strategies. Comprises six main components: databases, river simulation and management, agricultural planning, hydrologic modeling, remote sensing and user-model interface (Georgakakos, 2003).
Kafue decision support system	A hydrodynamic model (KAFRIBA-Kafue River Basin) has been developed to improve the operation of dams located upstream and downstream of the Kafue Flats, Zambia. Used in conjunction with improved forecasting of flows into the upstream reservoir, the decision support system enables the dam operators (Zambia Electricity Supply Company) to make decisions on releases in a systematic way that balances hydropower requirements with other water uses and protection of the ecology (and hence livelihood benefits) of the Kafue Flats (DHV, 2004).
Downstream Response to Imposed Flow Transformations (DRIFT)	In the Lesotho Highlands Dam Project, DRIFT was used to assess the impact of different flow release regimes on the river ecology and, via relationships determined between ecology and social benefits, the livelihoods of riverine communities.

Other definitions are not explicit about the use of computers and focus primarily on the objective of dss. For example:

[Dss] support decision-makers in solving problems that are poorly or insufficiently structured (Guariso and Werthner 1989)

This definition encompasses not only computer based systems but a wide range of methods, techniques and tools that can assist with decision-making. For example, the Building Block Methodology developed to evaluate the environmental flows required to maintain desired ecosystem features downstream of large dams (King *et al.*, 2000), would be classified as a dss by the latter definition. Another example of a non-computer based tool, though not specifically developed for dam planning and operation, is the River Basin Game developed to assist with resolution of conflicts over water abstraction in the Great Ruaha catchment, Tanzania. This game is effectively a role playing exercise based on the physical representation of a catchment in which marbles are used to represent the flow of water. The game, which is played as part of a two day workshop enables local users to reflect on the distribution of water in various situations and to assess the implications of different water management strategies for different stakeholder groups (Lankford *et al.*, 2004).

Over the last twenty years, new types of computer software have been developed that can be used to build dss. Originally developed to allow the impact of uncertainty about management systems to be accounted for in the decision making process, Bayesian networks are such tools (Jensen, 1996). Bayesian networks (sometimes called belief networks or casual probabilistic networks) provide a method for representing relationships between variables even if the relationships involve uncertainty, unpredictability or imprecision. Links between variables can be established deterministically or probabilistically using available data or, if more appropriate, expert opinion or local knowledge. By combining decision variables (i.e., variables that can be controlled) and utility variables (i.e., variables that should be optimized) into the relationships of a belief network it is possible to form a dss.

As far as is known, Bayesian networks have not been used for dam planning and operation in Africa. However, it is anticipated that they might be useful for managing dam releases, because they enable the integration of physical and socio-economic variables within a single modeling framework. They also allow inclusion of expert and local knowledge on the same basis as more objectively derived data. Hence the approach enables the creation of a model that may contain mathematical relationships as well as subjective elements corresponding to the experience of people who are an integral part of the system. The approach is based around drawing networks of interlinked variables and the essentially graphical nature of the method can facilitate formal discussion of the system structure with people from a wide variety of backgrounds and so encourages interdisciplinary discussion and stakeholder participation (Cain, 2001).

Challenge program project: improved livelihoods through dam management

The key objectives of the current Challenge Program project are to ascertain which types of dss are most appropriate for planning dams and managing the complexity of large dam operation and to determine how the participation of all stakeholders in the decision-making process is best facilitated. A key tenet of the project is that benefits derived from dams can only be optimized by planning and operating them with full consideration of the specific biophysical, social and economic context of the catchment in which they are located. The aim is to have integrated development that, within the constraints imposed by the system, combines the best of traditional practices and modern techniques and, as far as possible, maximizes benefits for those living both upstream and downstream of the dam (Figure 2).

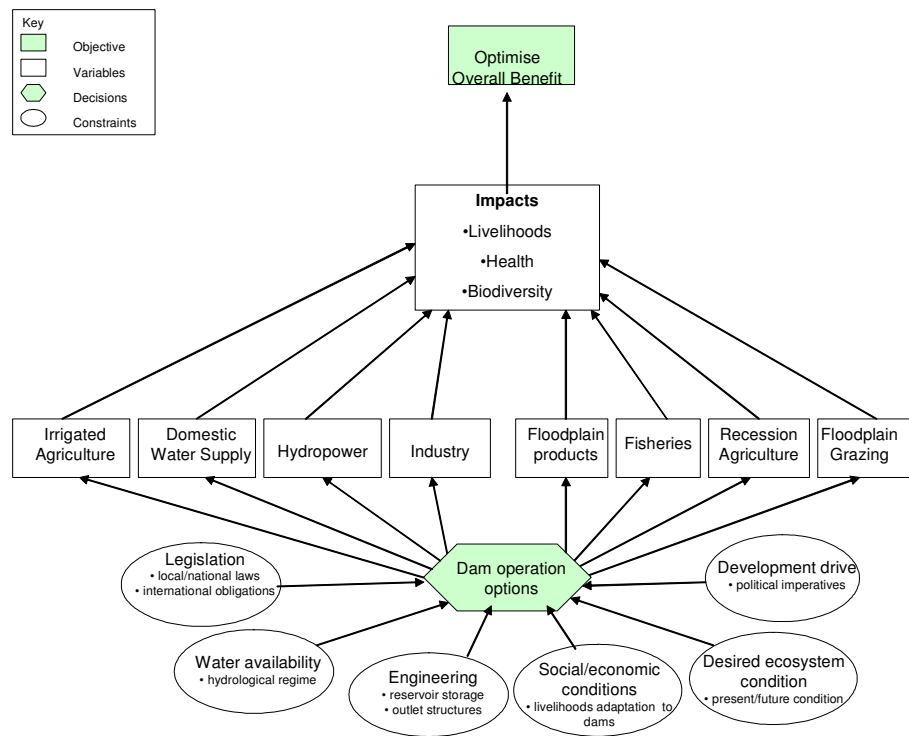


Figure 2: *Complex web of interlinked issues and trade-offs that must be taken into account in planning dam operation*

The study will be centered on two case studies conducted in Ethiopia. In conjunction with the dam operators, dss will effectively be field tested in each study. Stakeholder aspirations, system requirements and biophysical constraints will be used to determine a range of possible options for dam operation. As far as possible the dss will be set up in full consultation with local stakeholder groups and organizations. Thus configuring the dss will attempt to link expert opinion with input from local communities. In this way all

stakeholders will have considerable input to the configuration and content of the systems used.

The case studies have not yet been selected. However, a preliminary review of dam operation in Ethiopia, has highlighted that, for hydropower dams, operating rules have been designed primarily to maximize power generation. The dams are operated in a semi-integrated way, with those located in higher rainfall parts of the country drawn-down before those in more arid areas. In the past, consideration of local livelihood and environmental issues appears to have varied considerably. In some cases they were taken into account, but in others they were largely ignored (Hailu and Seleshi, 2005). Chara-Chara dam, a possible case study site, is located on the Nile at the outlet from Lake Tana. It was built to regulate flows for hydropower generation. However, a wide range of other water uses, including irrigation, water supply, environmental flows and tourism (i.e., discharges required to maintain flows over the Tis-Isat Falls) should be considered in optimizing its operation.

It is planned that the dss and research findings from the project will be used to transform predictions of different operating regimes into quantified descriptions of social, economic, environmental and health impact for all stakeholders. It is hoped that through provision of this information the dam operator will be able to optimize benefits in an equitable way. On the basis of insights gained from the study, a set of guidelines on the use of dss in the planning and operation of dams will be written.

Conclusion

Dams highlight the multi-dimensional nature of sustainable development and represent a microcosm of the challenges faced in water management. In their multi-purpose use dams bring the challenges of integrated water resources management together into a single point of focus. The social complexity of dam related conflicts is apparent in the kind and number of stakeholders involved; in conflicting interests, values or rights; in conflicting forms of knowledge, social norms and attitudes; in unequal power and influence of actors. Against this background, dss have a key role to play in assisting decision-makers improve dam planning and operation for the benefit of all stakeholders.

Key principles of dss to be used in dam planning and operation are that they should:

- facilitate examination of the wider social and ecological context of conflicts enabling mitigation and compromises to be found;
- enable integration of more and diverse sources of information from different scientific disciplines, but also include non-scientific inputs;
- sharpen the focus on stakeholder involvement in decision-making so that all stakeholders participate from early in the process;
- facilitate negotiation-based approaches to decision-making that hopefully lead to increased cooperation and consensus building between different stakeholders.

The range of functions provided by dams enables the provision of a variety of benefits and makes them a key part of water resource development. However, the diversity greatly complicates decision-making pertaining to dam planning and operation. The Challenge Program project aims to demonstrate the value of dss in contributing to improved development outcomes, ensuring public acceptance and reducing future conflict relating to dam planning and operation.

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